

## FIELD OF THE INVENTION

This invention relates to optical scanning devices such as bar code scanners, and more particularly to beam-shaping systems for generating a scanning laser beam adapted for use with a selected broad range of working distances and symbol densities.

## BACKGROUND AND OBJECTS

Bar code readers are known in the prior art for reading various symbologies such as UPC bar code symbols appearing on a label or on the surfaces of an article. The bar code symbol itself is a coded pattern of indicia comprised of a series of bars of various widths spaced apart from one another to bound spaces of various widths, the bars and spaces having different light reflecting characteristics. The readers in scanning systems electro-optically transform the graphic indicia into electrical signals, which are decoded into information, typically descriptive of the article or some characteristic thereof. Such information is conventionally represented in digital form and used as an input to a data processing system for applications in point-of-sale processing, inventory control and the like. Scanning systems of this general type have been disclosed, for example, in U.S. Patent No. 5,600,121, assigned to the same assignee as the instant application. Such systems may employ a portable laser scanning device held by a user, which is configured to allow the user to aim the device, and more particularly, a scanning laser light beam, at a targeted symbol to be read.

The light source in a laser scanner bar code reader is typically a semiconductor laser. The use of semiconductor devices as the light source is especially desirable because of their small size, low cost and low voltage requirements. The laser beam is optically modified typically by an optical assembly, to form a beam spot of a certain size at the target distance. It is preferred

that the cross section of the beam spot at the target distance be approximately the same as the minimum width between regions of different light reflectivity, *i.e.*, the bars and spaces of the symbol.

5 In the laser beam scanning systems known in the art, the laser light beam is directed by a lens or other optical components along the light path toward a target that includes a bar code symbol on the surface. The moving-beam scanner operates by repetitively scanning the light beam in a line, pattern or series of lines across the symbol by means of motion of a scanning component, such as a moving mirror placed in the path of the light beam. The scanning component may either  
10 sweep the beam spot across the symbol and trace a scan line across the pattern of the symbol, or scan the field of view of the scanner, or both.

Bar code reading systems also include a sensor or photo detector which detects light reflected or scattered from the symbol. The photo detector or sensor is positioned in the scanner in an optical path so that it has a field of view which  
15 ensures the capture of a portion of the light which is reflected or scattered off the symbol. The light is detected and converted into an electrical signal.

Some bar code reading systems are "retro-reflective". In a retro-reflective system, a moving optical element such as a mirror is used to transmit the outgoing beam and receive reflected light. Non-retro-reflective systems typically employ  
20 a moving mirror to transmit the outgoing beam and a separate detection system with a wide, static field of view.

Electronic circuitry and software decode the electrical signal in a digital representation of the data represented by the symbol that has been scanned. For example, the analog electrical signal generated by the photo detector is converted  
25 by a digitizer into a pulse or modulated digitized signal, with the widths corresponding to the physical widths of the bars and spaces. Such a digitized signal is then decoded, based on the specific symbology used by the symbol, into a binary representation of the data encoded in the symbol, and subsequently to the information or alphanumeric characters so represented. Such signal processors are

disclosed in U.S. Patent No. 5,734,152 assigned to Symbol Technologies, Inc. which patent is hereby incorporated by reference.

Different bar codes have different information densities and contain a different number of elements in a given area representing different amounts of encoded data. The denser the code, the smaller the elements and spacings. Printing of the denser symbols on an appropriate medium is exacting and thus is more expensive than printing symbols with larger elements. The density of a bar code symbol can be expressed in terms of the minimum bar/space width, also called "module size", or as a "spatial frequency" of the code, which is in the inverse of twice the bar/space width.

A bar code reader typically will have a specified resolution, often expressed by the module size that is detectable by its effective sensing spot. For optical scanners, for example, the beam spot size may be somewhat larger than the minimum width between regions of different light reflectivities, *i.e.*, the bars and spaces of the symbol. The resolution of the reader is established by parameters of the beam source or the detector, by lenses or apertures associated with either the beam source or the detector, by the angle of beam inclination with respect to the plane of the symbol, by the threshold level of the digitizer, by the programming in the decoder, or by a combination of two or more of these elements. The photo detector will effectively average the light scattered from the area of the projected spot which reaches the detector aperture.

The region within which the bar code scanner is able to decode a bar code is called the effective working range of the scanner. Within this range, the spot size is such as to produce accurate readings of bar codes for a given bar code density. The working range is dependent on the focal characteristics of the scanner components and on the module size of the bar code.

Many known scanning systems collimate or focus the laser beam using a lens system to create a beam spot of a given diameter at a prescribed distance. The intensity of the laser beam at this point, in a plane normal to the beam (ideally

approximately parallel to the scanned symbol), is ordinarily characterized by a "Gaussian" distribution with a high central peak. Gaussian beams typically have a profile along their axis of propagation exhibiting a waist (collimated) zone with limited divergence followed by a divergence zone thereafter. The collimated zone determines a depth of field (focusing range) for maximum bar code density. The working range is defined as the region within which the scanned beam spot is sufficiently well formed that its detected scattered radiation can be decoded by the scanner. But as the distance between the scanner and the symbol moves out of the working range of the scanner, which is typically only a few inches in length, the Gaussian distribution of the beam spot greatly widens, preventing accurate reading of a bar code. Such scanning systems, accordingly, must be positioned within a relatively narrow range of distances from a symbol in order to properly read the symbol.

It has been proposed to create a laser scan beam by directing a collimated beam of laser light onto a linear axicon optical element, for example, a conical lens, to produce a beam of light which exhibits a consistent spot size over a substantial distance along the axis of the beam. Such an optical system is disclosed in U.S. Patent No. 5,331,143 to Marom *et al.* and assigned to Symbol Technologies, Inc., which patent is hereby incorporated by reference.

The aforementioned axicon system produces a nearly diffraction free beam. The use of such a beam has been proposed to maximize the focusing limited working range of the scanning beam. Such a beam exhibits substantially no divergence over a relatively long distance range and then breaks into a donut like spot pattern of intensity distribution. Such a non-diverging beam can provide two to three times the range of a conventional Gaussian beam for a particular bar-code density. However, as noted by applicants, where such a beam is designed to improve performance in scanning a certain bar code density, the corresponding working ranges of lower density symbols are not increased significantly or at all,

being limited by the distance where the beam breaks into a donut-like distribution ("donut distance").

Accordingly, it is a primary object of the present invention to optimize and maximize the working ranges of a bar code scanner for a wide variety of bar code densities.

Some conventional scanners employ two laser optical systems: one a short working range system and the second a long working range system. Such scanners have multiple operating modes, which allow for the selection of a different optical system, spot sizes and scanning beam depending on the distance of the target system. However, such systems are larger and more complicated than single source scanners, and consequently tend to be more expensive and less desirable for all these reasons.

It is another object of the present invention to provide a compact and inexpensive bar code scanner with improved working ranges and variety in the bar code densities which can be read at such ranges.

It is known that in certain scanning applications, an elongated or elliptical spot may be used to improve the performance of the scanning system. *See*, for example, U.S. Patent No. 5,648,649 to Bridgelall. When an elliptical spot is employed, ideally the major axis of the spot is oriented parallel to the major axes of the bars making up the target code and perpendicular to the direction of beam scan. Such a spot form may reduce inaccuracies in reading the code, because, *e.g.* an elliptical spot system is somewhat less susceptible to errors introduced by voids and spreads in the symbol and speckle noise.

Conventionally, the elliptical spot is generated from a Gaussian distribution laser beam by introducing a cylindrical optical power in a direction perpendicular to the scanning direction and/or employing an elliptical or rectangular exit pupil. Applicants have observed that such techniques are ineffective in producing an effective spot geometry when an axicon laser beam is employed.

Accordingly, it is another object of the present invention to provide improved techniques for producing an elongated spot geometry in a laser scanning system employing both Gaussian and non-Gaussian laser beams.

5 In a bar code scanner which relies on a precise scanning laser beam profile and spot geometry, changes in temperature that affect the optical properties of the beam producing system can degrade the performance of the system such as by reducing effective working range, reducing readable code density at a particular distance and generally reducing the accuracy of the system. Various techniques have been proposed for reducing temperature variation ("athermalizing") optical systems in bar code readers. Such systems are disclosed, for example, in U.S. Patent No. 5,673,136 to Inoue and U.S. Patent Application Serial No. 09/109,018 filed July 1, 1998 to Li *et al.* and assigned to Symbol Technologies, Inc., which application is hereby incorporated by reference.

15 Typically glass optical elements are less affected by temperature changes than are plastic optical elements having the same nominal optical properties. Typically, also, plastic optical elements are less expensive and less difficult to fabricate and replicate.

20 It is a further object of the present invention to provide improved athermalized optical systems for laser scanners, both for conventional laser scanners and scanners adapted to achieve the other objects of the present invention.

These and other objects and features of the present invention will be apparent from this written description and the associated drawings.

## SUMMARY

The present invention relates to an improved axicon optical system for scanning optical codes. The improved beam-shaping systems of the present invention are capable of generating nearly diffraction-free beams to improve the ability to scan bar codes. A laser beam produced thereby has a central peak having a controlled divergence and may be used to produce an elongated scanning spot. Aspects of the present invention also relate to a laser assembly which may be used to produce scanning beams including the above-mentioned diverging beam with elongated spot. The apparatus combines various optical functions in structures which are relatively insensitive to temperature change.

The present invention includes an optical code scanner employing a diverging, nearly diffraction free laser beam to scan optical code symbols. The source of the laser beam may include a laser diode and an optical system positioned with respect to the laser diode and configured to produce a diverging laser beam with a generally conical wave front which flattens radially outwardly from an axis of propagation of the beam. In preferred embodiments, the nearly diffraction-free beam has an elongated transverse intensity distribution which forms an elongated spot on a reference surface perpendicular to an axis of propagation of the beam at a minimum working distance from the scanner. The central peak in the transverse intensity does not split into rings or donuts within the designed working range. For example, the beam produces a spot at the minimum working distance of the scanner which has a dimension  $d_0$  in the direction of scanning which is less than 13 mils and a dimension  $d$ , greater than 160 mils at the maximum working distance of the scanner. For example, embodiments of the scanner are capable of using the laser beam to read 7.5 mil code at a minimum working distance of less than 9 inches and to read 100 mil code at a maximum working distance greater than 520 inches.

The present invention also includes a laser beam for use in scanning bar codes. The inventive beam has a wave front which deviates from a reference plane perpendicular to its axis of propagation, the deviation being characterized by a phase whose dependence is given by

$$W(r) = \alpha r - \beta r^2$$

where  $W(r)$  is the deviation; where  $r$  is radial distance from the axis of propagation; where  $\alpha$  is selected to produce a spot at the minimum scanning distance with a diameter  $d_0$  sufficient to permit the reading of the highest density bar code to be scanned; and where  $\beta$  is selected to provide optimum working ranges for bar codes of different densities. In preferred embodiments,  $\alpha$  is selected between  $0.2 \times 10^{-3}$  and  $6 \times 10^{-3}$ .  $\beta$  is selected so that

$$\frac{\lambda}{10 \cdot R_0^2} < \beta < \frac{2 \cdot \alpha}{R_0}$$

where  $\lambda$  is the laser wavelength, where  $R_0$  is the starting radius of the laser beam at the system aperture. More preferably,

$$\frac{\alpha}{5 \cdot R_0} < \beta < \frac{\alpha}{R_0}$$

The present invention also teaches the construction of an optical system having at least one optical element for partially collimating the laser beam, providing optical power to reduce beam divergence and for producing a wave front as described in Equation 24 below. In preferred embodiments, the optical system includes a plano convex lens for partially collimating the laser beam and an optical element having a substantially flat first surface perpendicular to the optical axis of the system and a second surface defined by a figure of rotation formed by rotating



a line about the optical axis at an acute angle to define an optical element which causes a phase tilt in the beam inward toward the optical axis. The beam so produced has a transverse field distribution that can be expressed as a series containing the Bessel functions. Essentially only the axial peak of beam is employed for scanning.

The present invention also includes a method of producing a laser beam for scanning an optical code. A diverging laser beam is provided by a semiconductor laser. The divergence of the laser beam is reduced by, for example, a lens to a predetermined non-zero divergence. A generally conical wave front deformation is imposed on the laser beam, for example by a lens with a conical surface. These steps can be performed in any order or simultaneously. Such a diverging axicon laser beam is produced for scanning optical code. The beam may be used in a method of scanning a symbol. According to this method, a beam of laser light is generated. The transverse intensity pattern of the beam shows a central peak surrounded by a plurality of side lobes symmetrically located on either side of the central peak. The beam has a high degree of energy confinement near the propagation axis when the beam travels to the symbol. The modified beam may be moved across the symbol to scan the symbol.

Another aspect of the present invention relates to a laser scanner apparatus for producing a laser beam with an elongated spot for scanning a symbol. The apparatus includes the use of a partially reflective mirror, which is placed in the optical path of a circular or non-circular diffraction-free beam. Light is partially transmitted and partially reflected. However, the reflected portion of the beam returns to the same direction as the transmitted beam by a second reflection on the back of the mirror. A nearly diffraction-free beam is obtained with an elongated transverse intensity distribution by a superposition of the two portions of the incident beam. Advantageously, the two portions are sufficiently displaced so that optical interference of these two portions is negligible. Centers of the beam portions may be displaced from one another along an axis perpendicular to a

direction of scanning of the laser scanner apparatus. The result is an elongated region of illumination on a reference plane perpendicular to the beam portions in at least part of a working range of the laser scanner apparatus. Advantageously, the beam portions are sufficiently displaced so that they have minimum overlap. Preferably, the optical system used to produce the elongation is a single period diffraction grating with a cosine-shaped profile.

In an alternative embodiment, the optical system includes an optical plate having two planar refractive surfaces which are non-parallel and from each of which a portion of the laser beam is propagated. In yet another alternative embodiment, the optical system includes a partially reflective plate having two planar reflective surfaces from each of which a portion of the laser beam is propagated.

The present invention also contains techniques for enhancing the temperature stability of the laser beam source. A lens system may be employed having a glass lens with at least one spherical surface; and a molded plastic element having a non-planar refractive surface located on an optical axis of the glass lens. The combination of the plastic lens and the glass lens provides an aspherical lens system with essentially all of the optical power in the glass lens and with greater temperature stability than an optically equivalent aspherical plastic lens. The plastic element may include at least one surface configured to produce the generally conical wave front deformations described herein. The molded plastic element may also provide a single period grating or provide an aberration correction for the glass lens. Preferably, rotationally symmetric elements can be formed on one surface of the plastic element, and cylindrical elements can be formed on the other surface.

An athermalized laser assembly may be constructed from a laser diode, a lens system, and first and second members for maintaining the relative positions of the laser diode and lens system. The first member may be a tube having a first coefficient of thermal expansion and effective length  $L$  in the direction of an

optical axis of the laser assembly. The second member may be a cylindrical sleeve. The sleeve may have a second, larger coefficient of thermal expansion and an effective length  $L_p$  in the direction of the optical axis of the laser assembly. The sleeve and tube may be telescoping and together confine the separation between the laser diode and lens system to a desired spacing along the optical axis of the assembly. The lengths  $L$  and  $L_p$  and the thermal properties of the tube and sleeve are selected so that linear expansion of the sleeve in one direction along the optical axis of the assembly substantially cancels out the linear expansion of the tube in the opposite direction.

The laser assembly may be constructed with a lens system which includes a lens with at least one spherical surface. A lens element integral with the sleeve provides a conical surface and a single period diffraction grating with a cosine-shaped profile. The laser diode and lens system may be positioned with respect to one another and configured to produce a diverging, nearly diffraction free beam having an elongated region of illumination in a reference plane perpendicular to the laser beam within a working range of the laser assembly.

The foregoing is intended to summarize certain aspects of the invention. The subject matter intended to be protected is, however, defined by the claims and equivalents thereof.

#### BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a pictorial cut away view of a hand held laser scanner illustrating certain aspects of the present invention;

Figure 2 is a diagram showing a wave front and ray structure of a prior art non-diverging axicon beam;

Figure 3 is a diagram showing the approximate beam profile of a prior art non-diverging axicon beam;

Figure 4 is a diagram showing a wave front and ray structure of a laser beam of a preferred embodiment of the present invention;

Figure 5 is a diagram showing the approximate beam profile of a beam of a preferred embodiment of the present invention;

5        Figures 6(a) through (h) are examples of various combinations of optical elements which may be employed to produce a diverging, nearly diffraction free beam of a preferred embodiment of the present invention;

Figures 7(a) and 7(b) illustrate the use of optical elements to produce an elongated spot from a laser beam in accordance with the present invention;

10       Figure 8 illustrates the combination of optical elements including a cosine profile optical surface for stretching the spot produced in an optical system in accordance with a preferred embodiment of the present invention;

15       Figures 9(a) and (b) illustrate the beam diameter and modulation transfer function (MTF) of a laser scanning beam in accordance with a preferred embodiment of the present invention;

Figures 10 through 14 illustrate laser spot characteristics of the beam of Figure 9 at various working distances including intensity distribution (a), spread function (b) and MTF (c);

20       Figure 15 is a cross-sectional view of a glass lens and plastic aberration corrector in accordance with a preferred embodiment of the present invention;

Figure 16 is a cross-sectional view of a prior art lens and laser diode structure;

Figure 17 is a cross-sectional view of an athermalized laser assembly using a plastic element;

25       Figure 18 is a cross-sectional view of an athermalized optical system for producing diverging, nearly diffraction free beams including stretched beams in accordance with preferred embodiments of the present invention; and

Figure 18(a) is a detail of a plastic element used in the optical system of Figure 18.

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## DETAILED DESCRIPTION

The present invention provides novel and useful laser beams with profiles and spot geometries which can be adapted to optimized working ranges and code densities according to the intended use of the laser scanner. The present invention also provides optical systems for producing such laser beams. The systems are readily fabricated and thermal stable.

Figure 1 is a pictorial cut away view of a hand held laser scanner device 20 illustrating certain aspects of the present invention. The device is usable in reading symbols including the one dimensional bar code symbol 22. It will be understood that aspects of the present invention may also be used in reading two dimensional optical code symbols such as PDF code and MaxiCode.

The laser scanner device 20 given as the example here, is of a type having a housing 24 with a barrel portion 26 and a pistol grip handle portion 28. The present invention may also be implemented in other types of scanners including stationary point of sale units, pen scanners, ring scanners, etc.

In the illustrated embodiment, the barrel portion 26 of the housing is formed with an exit port or window 30 through which an outgoing laser light beam 32 passes. The beam 32 is shown impinging on the bar code symbol 22, at a distance from the scanning device.

The laser beam 32 scans across the bar code symbol 22 along a path A-A which, at least under ideal conditions is perpendicular to the principle axes of the bars and spaces making up the symbol 22. This linear scanning movement of the laser beam 32 is generated by an oscillating optical element such as the pivoting mirror 34 shown in the embodiment of Figure 1. If desired, driving mechanisms may be provided to scan the beam 32 through a two dimensional scanning pattern to permit reading of two dimensional bar code symbols.

The scanner device 20 includes a source of laser light such as the laser diode 36 shown in the embodiment of Figure 1. The laser diode may be mounted

in a tube 38, which in turn is positioned in the housing. A photo detector (not shown) is provided within the housing to receive at least a portion of the light reflected by the bar code 22. The photo detector may face outwardly through the window 30, or, alternatively may face the scan mirror 34 to receive light reflected from the symbol 22. The photo detector detects light reflected from the symbol 22 and creates an analog electrical signal. A digitizer and decoder processes signals from the photo detector in the conventional way to derive information from the symbol 22.

The laser diode produces a laser beam which, in the embodiment of Figure 1, is directed onto a lens 40 and a linear axicon lens 42. The appropriate selection of lens surfaces and component placements as well as various alternative embodiments are discussed in detail below. The beam 32 has a central peak which will produce a spot of a size which increases with distance from the scanner -- a diverging beam. The central spot is largely unaffected by diffraction effects. These and other important properties of the beam are also discussed in detail below.

In the embodiment of Figure 1, the laser beam exits the tube 38 and is reflected off of a folding mirror 44 toward the scan mirror 34. The scan mirror is pivoted in the direction indicated by the double-headed arrow B-B to produce a desired beam scanning pattern. The system can read codes close to the system of some maximum density and has a maximum working distance which may be dictated by the donut distance  $Z_{\max}$ , discussed below.

## I. Laser Beams For Versatile Code Reading Systems

Preferred embodiments of the present invention employ a laser beam having wave front deformation at a reference plane perpendicular to an optical axis of the system at, for example, an exit pupil of focusing system. The deformed wave front is described by the following formula:

$$W(r) = \alpha \cdot r - \beta \cdot r^2 \quad (1)$$

where

$$\beta > 0 \quad (2)$$

and where  $r$  is the radial distance from the optical axis and  $\alpha$  is the cone angle of the wave front cone as defined below.

To understand properties and advantages of the beam (1), consider first propagation of an infinite conical wave (non-diverging axicon beam) such as described in the above-mentioned '143 patent to Marom *et al.* The properties of such a beam are shown in Figures 2 and 3. The wave front of the beam can be described by deviation from the reference plane by an equation of the form:

$$W_0(r) = \alpha \cdot r \quad (3)$$

It is known that such a wave produces a non-diverging Bessel beam. The diameter of the beam central peak  $d_0$  is determined by the wave length  $\lambda$  and wave front cone angle  $\alpha$ :

$$d_0 = 0.76 \cdot \lambda / \alpha \quad (4)$$

Although the theoretically infinite Bessel beam does not change with distance, its intensity is equal to zero, so that energy is conserved.

For bar code scanners, an essentially non-divergent axicon-like laser beam that are close to a Bessel beam bounded by a Gaussian envelope had been proposed in the '143 patent providing larger working ranges than conventional Gaussian beams. Consider such a laser beam as shown in Figures 2 and 3 having at a starting distance ( $Z=0$ ), on the axis of propagation C-C, radius  $R_0$  and a conical wave front (50). Similar to the theoretical Bessel beam, this beam propagates



practically with zero divergence. However, the beam intensity is not zero any more. The price paid is that the beam breaks into a donut shaped intensity distribution after distance  $Z_{\max 0}$ .  $Z_{\max 0}$  is given by the expression:

$$Z_{\max 0} = R_0 / \alpha \quad (5)$$

The scanner has working ranges on high and low density bar codes limited by the distance  $Z_{\max 0}$ . Obviously, in order to increase working range of the beam, one could increase  $Z_{\max 0}$  by increasing the beam radius  $R_0$ . A limitation here comes from the fact that the larger  $R_0$ , the less relative energy goes into central maximum  $d_0$ , and the lower the Modulation Transfer Function (MTF) of the scanning laser beam. In practice,  $R_0$  may, for example, be a physical aperture such as a circular or elliptical mask or be dictated by the size of the beam produced by the laser and lens system.

In accordance with the present invention, a wave front deformation is performed consistent with equation 1. Such a wave front 52 is shown in Figure 4. The wave front 52 is generally conical and flattened at its radial edge. One form of the wave front is a shape generated by rotating a curved line 53 at an acute angle  $\alpha$  about the axis of propagation D-D of the system. The form of the line may be selected to produce a nearly conical wave front near the axis D-D and to produce a flattening toward reference plane 54 in radially outward portions of the wave front 52 closer to the edge of the aperture.

One way to produce this beam is to transform the beam of equation 3 using a lens with a focal length of  $F = -1/(2\beta)$  in the reference plane  $Z=0$ . One can understand this transformation based on the lens function: the plane wave front is transformed into a spherical one with radius equal to  $F$ . In other words, the lens introduces a wave front deviation equal to sag of the sphere with radius  $F$ . For  $r \ll F$ :

$$\Delta W(r) = (F^2 + r^2)^{0.5} - F = F \cdot (1 + r^2/F^2)^{0.5} - F \approx F \cdot (1 + 0.5 \cdot r^2/F^2) - F = 0.5 \cdot r^2/F$$

If

$$F = 1/(2\beta) \quad (6)$$

Then

$$\Delta W(r) = -\beta \cdot r^2, \text{ and } W(r) = W_0(r) + \Delta W(r) \quad (7)$$

The profile of beam  $W(r)$  can be determined by following the rule of geometrical optics: The intensity distribution that takes place in the beam  $W_0(r)$  at a distance  $Z_0$  will take place also in the beam  $W(r)$  but at different distance  $Z$  with magnification  $M=Z/Z_0$ . According to the lens formula:

$$1/Z - 1/Z_0 = 1/F = -2 \cdot \beta \quad (8)$$

$$d/d_0 = M = Z/Z_0 = 1 - Z/F = 1 + 2 \cdot \beta \cdot Z \quad (9)$$

Beam  $W_0(r)$  does not diverge until donut distance  $Z_{\max 0}$  (see Fig. 3). According to (5), (6), and (8), donut distance of the beam  $W(r)$  will be determined by:

$$Z_{\max} = Z_{\max 0} \cdot F / (F + Z_{\max 0}) = R_0 \cdot F / (R_0 + F \cdot \alpha) = R_0 / (\alpha - 2 \cdot \beta \cdot R_0) \quad (10)$$

Within  $0 < Z < Z_{\max}$ , the profile of the beam of equation (1) can be determined using equation (9):

$$d = d_0 \cdot (1 + 2 \cdot \beta \cdot Z) \quad (11)$$

The profile of the central portion of this beam along the axis of propagation D-D is shown in Figure 5. As indicated by equation d is essentially independent of aperture size. As shown in Figure 5, the beam diverges approximately linearly.

The profile slope is, in effect, a beam magnification caused by the lensing. The divergence of the beam of Figure 5 is two to three times less than the divergence of a truncated Gaussian beam with comparable source and beam radius. Unlike a Gaussian beam, the diameter  $d$  of the central peak is not appreciably affected by the system aperture  $R_0$  or the diffraction caused thereby. Although the

beam profile may contain side lobes, the sharpness and diameter  $d$  of the central peak may be controlled through the working range of the system. Diffraction does not appreciably affect the spot with distance from the scanner and the central peak is largely determined by geometric effects rather than diffractive effects.

Equations (10) and (11) show advantages of the proposed beam of Equation (1) over the known non-diverging axicon beam of Equation (3):

(a) The donut distance is increased or the donut effect is eliminated completely, as indicated by the following expressions:

$$\begin{aligned} Z_{\max} &= R_0/(\alpha - R_0 \cdot 2\beta) > Z_{\max 0}, & \text{if } 0 < \beta < \alpha/(2R_0) & \quad (12) \\ Z_{\max} &= \infty & \text{if } \beta = \alpha/(2R_0) & \quad (13) \end{aligned}$$

The increased donut distance  $Z_{\max}$  of the beam of equation (1) permits the increase of working ranges simultaneously for high and low-density bar codes. Note that the beam does not break into donut at all if  $\beta > \alpha/(2R_0)$  because  $Z_{\max}$  becomes negative.

(b) The central peak diameter  $d$  of the laser beam of equation (1) changes approximately linearly with distance  $Z$  from the reference plane ( $Z=0$ ) (see Figure 5), in accordance with the relation

$$d(Z) = d_0 \cdot (1 + 2 \cdot \beta \cdot Z) \quad (14)$$

where  $d_0$  is determined by equation (4). The linear increase of the scanner ranges with the decrease in bar code density is a useful feature of the present invention given that it is natural to scan larger bar codes from greater distances.

The following procedure can be used to choose the coefficients  $\alpha$  and  $\beta$  to provide an optimum combination of working ranges for a variety of bar code densities:

- (1) Choose a maximum starting beam radius  $R_0$  (100% encircled energy) and central maximum diameter  $d_0$  based on the signal processing requirements for reading the highest density bar code to be read by the system.
- (2) Calculate  $\alpha$  from equation (4).
- (3) Determine  $\beta$  based on optimum trade-off between working ranges for high-density and low-density bar codes. A preferred upper limit for  $\beta$  is  $< \frac{2\alpha}{R_0}$ , more preferably  $\beta < \frac{\alpha}{R_0}$ .

The following Table I illustrates difference between working ranges of a non-diverging axicon beam ( $\beta=0$ ) and two diverging beams of the present invention. In all cases,  $\alpha=1.4 \cdot 10^{-3}$ ,  $R_0=1.75$  mm, and optimum laser bar code signal processing is assumed using a first derivative signal processor.

Table I

Bar-code module, mil	Working ranges in inches		
	$\beta=0$	$\beta=0.4 \cdot 10^{-3} \text{ mm}^{-1}$	$\beta=0.6 \cdot 10^{-3} \text{ mm}^{-1}$
4	-	-	-
5	11	-	-
7.5	30	30	15
10	44	58	35
15	49	94	80
20	56	120	110
40	48	200	240
55	56	265	340
70	60	320	435
100	60	420	627

After having  $\alpha$  and  $\beta$  determined, known optical design components may be used to generate wave front (1) based upon desired location of exit pupil, axicon vertex position relative to the exit pupil, and other optomechanical constraints. Some of the possible optical systems for producing the beam of Figures 4 and 5 are shown in Figure 6.

Figures 6(a) through 6(h) are ray traces of marginal and axial rays in various optical systems for producing the diverging nearly diffraction free beams of the present invention. In each Figure in which they appear, element 100 is a laser diode, element 102 is a plano-convex negative lens and element 104 is a linear axicon lens (*i.e.* lens with a plano surface and a conical surface of revolution made by rotating a straight line at an angle  $\theta=\alpha/(n-1)$  about the optical axis E-E,

where  $n$  is the index of refraction of the material out of which the linear axicon lens is made.

The optical system of Figure 6(a) employs a spherical collimation lens 102, a linear axicon lens and a plano-concave positive spherical lens 106, all located on the optical axis EE. Advantageously, the laser diode 100 and collimation lens 102 may be part of a laser diode package. The laser beam from the collimation lens next impinges on the linear axicon lens where its wave front is deformed from a planar shape (coplanar with the plano surface of the linear axicon lens 104) to a conical shape as described above. The beam from the linear axicon lens is further deformed by the lens 106 and defocused to form the diverging axicon beam of a preferred embodiment of the present invention.

In the optical system of Figure 6(b) the collimation lens and linear axicon of Figure 6(a) have been merged into a single optical element 108 which performs the functions of elements 102 and 104 of Figure 6(a). The surface of the element 108 is a composite of the surface heights of non-planar surfaces of elements 102 and 104 of Figure 6(a).

In the optical system of Figure 6(c) the lens 102 and distance  $d$  from the effective point source origin of the beam from the laser diode 100 are selected to partially collimate and focus the laser beam to produce a wave front with a deformation of  $-\beta r^2$  from a reference plane parallel to the plane back surface of lens 102. In other words, the divergence of the beam 120 from the assumed point source is reduced to a lesser, non-zero divergence at 122.  $R_0$  denotes the system aperture.

In the optical system of Figure 6(d), the linear axicon lens has been reversed from the orientation shown in Figure 6(c). However, the optical system functions in essentially the same way as that of Figure 6(c), to produce a diverging beam of a preferred embodiment of the present invention.

In the optical systems of Figures 6(e) and (f) the positions of the linear axicon lens 104 and the lens 102 have been reversed over those shown in the

preceding Figures. Also, the physical cone angle of the conical surface of the lens 104 is somewhat larger than that of linear axicon surfaces of Figures 6(a)-(d), in order to produce a diverging beam similar to that produced by the optical systems of those preceding Figures. The resultant system of Figures 6(e) and 6(f) have a reduced depth, x, which may be advantageous in applications where compactness of the optical assembly is important to the overall design.

In the optical systems of Figure 6(g), the lens surface and linear axicon surface have been merged to produce surface 110 of optical element 112. The system of Figure 6(h) employs a lens 114 with linear axicon back surface 116 and a negative power spherical surface 118. In both systems, the component separation, negative power and physical cone axis of the axicon are selected to produce a diverging axicon beam in accordance with equation (1).

From the foregoing, it will be apparent that there are many equivalent optical structures for producing the laser beam of the present invention. It will be understood by persons skilled in the optical design arts that such implementations may include mirrors, diffractive elements, gratings, or volume holographic bodies.

## **II. Radially Elongated (Stretched) Laser Beams And Associated Optical Systems**

As noted above, the advantages of using an elliptical spot in laser bar code scanning is well-known. Frequently this spot shape is produced with a cylindrical lens. However, applicants have observed that this common mechanism for producing ellipticity in Gaussian beams is not suitable for use with axicon beams. Instead of the desired elliptical beam in the near field and circular beam in the far field, the result is a round spot in the near field and multiple spots at far distances.

In accordance with the present invention, instead of using cylindrical power, the laser beam may be split in vertical direction. Beam splitting can be achieved by using a diffraction grating or various refractive or reflective surfaces. These embodiments will now be described.

A first approach for obtaining an expanded beam width in a direction orthogonal to the scanning, is to generate replicas or portions of the beam, via a beam-splitter, tilted plate, etc., (see Figures 7(a) and 7(b)). This achieves an expanded beam front without significantly affecting other properties of the original beam. Care needs to be taken to ensure that the interference between the beams at their fringe regions when they do partially overlap, does not adversely affect the performance of the scanner.

One way of stretching a beam is to use a mirror to split the incident beam and overlap the beam portions as shown in Figures 7(a) and 7(b). As shown in Figure 7(a), a mirror 200 which may be the scan mirror has a beam splitting surface 202 and reflective surface 204. An incoming beam 206 will be split into at least two beams: 208 and 210. Surfaces 202 and 204 are tilted at a small angle  $\theta$  from parallel. Therefore, beams 208 and 210 will not be parallel. The small angle between beams 208 and 210 provides the elongated or stretched laser spot.

Another method of generating an elongated beam is illustrated by the embodiment of Figure 7(b). A partially reflective mirror 220 is placed at an angle in the optical path of a beam 222, particularly the diverging nearly diffraction free beam previously discussed. Light is partially transmitted and partially reflected as indicated by the rays at 224 at the optical interface 226. For example, the surface at 226 may be 50% silvered. Light reflected at the interface 226 may be re-reflected at interface 228, which may be an essentially 100% reflective surface. The result may be two partially overlapping beam portions 230 and 232. The separation distance  $S$  between the centers of the beam portions, advantageously, remains constant through the working range of the scanner. Alternative beam portions 234 and 236 are also shown which are separated so that there is no overlap of their central maxima, hence no appreciable interference effects. In this embodiment, the dimension of the spot, perpendicular to the scanning direction is effectively doubled.



A preferred method of producing an elongated or stretched beam makes the use of what may be thought of a diffraction grating. The approach is based on a device consisting of a <sup>6</sup>course (low spatial frequency) grating positioned over the beam aperture. This could be achieved with an amplitude grating (which is partially absorbing, thus reducing the power throughput) or a phase grating (which is non-absorbing, and can provide greater beam stretching in view of the many diffraction orders that it contains). In the following embodiments, systems are described using a simple uniform aperture. Nevertheless, the results are expected to be similar for arbitrarily shaped apertures.

In a preferred embodiment, beam elongation is achieved using a very small diffracting angle which corresponds to only one period of a grating defined by the equation:

$$W(y) = W_0 \cdot \cos\left(\frac{y}{A} \cdot 2\pi\right) \quad (15)$$

where  $W$  is the grating phase,  $y$  is the lateral coordinate perpendicular to the scanning direction,  $A$  is the vertical aperture, and  $W_0$  is the amplitude of the grating phase.

Equation (15) describes a cosine surface. Its optical power over the aperture is equal 0. As will be seen in the example presented below, this technique generates a smooth elongated spot in the near field. The technique is useful in application to axicon beams lacking inherent ellipticity. It is also useful in adding ellipticity to other conventional beams.

A system for producing an elongated, diverging beam is illustrated in Figure 8. The system consists of a laser beam source 250, positive lens 252, linear axicon lens 254 and lens 256 having a surface 257 generated by a line perpendicular to the optical axis F-F which tracks the cosine curve of equation (15). It will be observed that the components and their arrangement in Figure 8 are similar to Figure 6(c) discussed above, but with the addition of the cosine surface

lens 256. The resultant beam propagates in a direction along optical axis F-F. The spot 258 is stretched or elongated in the y direction.

The following is a theoretical evaluation of the use of a grating to achieve beam elongation. Let a flat aperture (1-D) be defined as "rect (x/a)" which is equal to 1 for  $|x| < a/2$  and 0 elsewhere. Then in the "far field" one gets

$$\text{rect}\left(\frac{x}{a}\right) \Leftrightarrow a \sin c(af_x) \quad (16)$$

where

$$\sin c(af_x) = \frac{\sin(\pi af_x)}{\pi af_x} \quad (17)$$

Multiplying this function with an amplitude coarse grating (of period "a"):

$$t(x) = \frac{1}{2} \left[ 1 + \cos\left(2\pi \frac{x}{a}\right) \right] \quad (18)$$

one gets in the far field

$$\text{rect}\left(\frac{x}{a}\right)t(x) \Leftrightarrow \frac{a}{2} \left[ \sin c(af_x) + \frac{1}{2}(\sin c(af_x - 1) + \sin c(af_x + 1)) \right] \quad (19)$$

On the other hand, when a phase grating is used, its transmittance is expressed as

$$t(x) = e^{i\gamma \cos\left(2\pi \frac{x}{a}\right)} \quad (20)$$

Incidentally such a grating may be achieved either by diffractive means (DOE) or refractive ones. The relation between  $\gamma$  and the physical height  $G$  of the grating variations is

$$\gamma = 2 \frac{\pi}{\lambda} (n-1) G \quad (21)$$

5 where  $\lambda$  is the light wavelength and  $n$  the index of refraction of the material, assumed to be surrounded by air ( $n=1$ ).

Since the phase grating has also a periodicity " $a$ ", it can be expanded in a Fourier series, thus leading to

$$e^{i\gamma \cos(2\pi \frac{x}{a})} = \sum_n J_n(\gamma) e^{i2\pi n x/a} \quad (22)$$

10 where  $J_n$  is the Bessel function of order  $n$ . Thus, when a phase mask multiplies the input, one gets in the far field:

$$\text{rect}\left(\frac{x}{a}\right) e^{i\gamma \cos(2\pi \frac{x}{a})} \Leftrightarrow a \sin c(af_x) * \sum_n J_n(\gamma) \delta(f_x - \frac{n}{a}) = a \sum_n J_n(\gamma) \sin c(af_x - n) \quad (23)$$

15 The result thus consists of several replicas of the original pattern propagating along the different diffraction orders and weighted according to the depth of the grating corrugation.

As noted above, it is proposed to use a defocused beam with wave front at the exit pupil:

$$W(r) = \alpha \cdot r - \beta \cdot r^2, \quad (1)$$

where  $r$  is the radial coordinate,  $\alpha$  is the cone coefficient, and  $\beta$  is the defocus coefficient. To achieve beam stretching, the laser beam is elongated in the direction perpendicular to the scanning using a one-period diffraction grating which, in generalization, can be expressed in the form:

(15a)

where  $W(y)$  is the phase delay suffered by the wave at coordinate  $(y)$  in passing through the element,  $A$  is the linear dimension of the aperture in the  $y$ -direction and  $M$  is an integer. In the preferred case of  $M = 1$ , Eq. (15a) reduces to the form

$$W(y) = w_1 \cos \left( 2\pi \frac{y}{A} \right). \quad (15b)$$

where  $y$  is the vertical coordinate,  $A$  is the vertical aperture dimensions, and  $w_1$  is the amplitude of wave front deformation.

Combining equations (1) and (15), the optimum diverging elongated beam can be obtained when using the following wave front deformation at the system exit pupil:

$$W(x,y) = a\sqrt{x^2 + \varepsilon y^2} - \beta(x^2 + y^2) + \sum_{m=1}^M w_m \cos \left( 2m\pi \frac{y}{A} \right) + \gamma y^2 \quad (24)$$

The following values are typical:

$$\alpha = (0.2 - 6) \times 10^{-3}; \varepsilon = 1; \gamma = 0;$$

and

$$\frac{\lambda}{10R_0^2} < \beta < 2\frac{\alpha}{R_0}$$

The following example illustrates the properties of a beam generated in accordance with equation (24) optimized for variety of bar-code densities ranging from 7.1 mil to 100 mil and having spot ellipticity up to 110 inches from exit pupil. The beam is predicted to provide the following working ranges (measured from exit pupil):

Bar-code module, mil	Working range, inches
7.5	From 8.5 to 25
10	From 8.5 to 42
15	to 81
20	to 112
40	to 240
55	to 330
70	to 420
100	to 600

Beam parameters (x is scanning direction, y is perpendicular one):

(a) Laser

- wavelength: 635 nm
- divergence angles: 8° x 28° (x x y)

- (b) Lens
- focal length: 9.2 mm
  - aperture: 3 x 2.5 mm (x x y)
- (c) Wave front deformation parameters:
- cone angle coefficient  $\alpha=1.4 \cdot 10^{-3}$
  - defocus coefficient  $\beta=0.6 \cdot 10^{-3} \text{ mm}^{-1}$
  - amplitude y-axis  $W_0=380 \text{ nm}$

Figure 9(a) shows the Focusing Profile of the laser beam and Figure 9(b) shows MTF of the system. The focusing profile illustrates how beam diameter (in microns) diverges as distance (in inches) from the scanner increases. Beam diameters in the horizontal (scanning) and vertical planes are calculated at 50% intensity level. Figure 9(b) illustrates how the MTF of the system varies with code density and distance.

Figures 10-14 show laser spot characteristics at various working distances: 8.5, 25, 81, 112 and 600 inches, respectively. In particular, Figure 10 illustrates laser spot characteristics at a minimum working distance of 8.5 inches. The size and elongation of the spot is illustrated by the intensity distribution of Figure 10(a). The intensity profile of the spot is shown along the x and y axis in the graph of the Line Spread Functions (LSF) in Figure 10(b). It will be observed that the effective spot dimension in the y-direction is greater than in the x direction *i.e.* the spot is elongated. The horizontal MTF at 8.5 inches is presented as a function of bar code module size in mils in Figure 10(c).

Similar data is presented for the same beam at greater working distances in Figures 11-14 which represent maximum working distances for 7.5 mil, 15 mil, 20 mil and 100 mil bar code modules, respectively. It will be observed that the y axis elongation or stretching of the spot is substantially greater at short working distances and gradually diminishes as working distance increases.

### III. Plastic Aberration Corrector For Glass Lenses

The most economical way for mass producing aspherical lenses is plastic molding. However, the strong temperature dependence of the refractive index of plastic causes undesirable lens focal plane shifting with temperature. Therefore, plastic lenses are typically not used in applications where stable focal distance is required over a wide temperature range.

There are several known mass production methods to make temperature-stable aspherical lenses for laser beam transformations (collimating, focusing, etc.):

- (a) spherical glass lens with attached plastic aspherical replica;
- (b) aspherical glass molded lens;
- (c) plastic athermalized aspherical lens using combination of diffractive and refractive optical power.

The first two methods use specialized optical technology that may lead to an increased part price. The third type of lens system suffers from energy losses at the diffractive surface.

It is an object of the present invention is to provide a high-quality, cost-effective, mass producible and temperature-stable aspherical lens system. The technique is advantageously used in both conventional laser bar code scanners and in scanners using the elongated, diverging laser beams disclosed herein.

In accordance with the present invention, a spherical glass lens is used with a separate plastic phase plate for aberration correction. In the simplest embodiment, all optical power is provided by a stable glass component. The phase plate has little or no optical power and provides correction of the spherical aberrations of the lens. Optical path difference (OPD) introduced by a refractive component into the transmitted wave front is determined by the component refractive index  $n$  and thickness  $t$  as function of radius  $r$ :

$$W(r) = (t(r)-t(0)) \cdot (1-n) \quad (25)$$

Change of OPD due to temperature dependence of refraction index is given by the expression

$$\Delta W = \Delta T * \frac{\partial W}{\partial n} \frac{\partial n}{\partial T} = \Delta T * \frac{\partial n}{\partial T} \cdot \frac{W}{n-1} \quad (26)$$

The smaller the nominal OPD (W) introduced by the refractive component is, the less the wave front distortion  $\Delta W$  caused by temperature dependence of refractive index  $\partial n / \partial T$  is. This is why a plastic component having high coefficient  $\partial n / \partial T$  can be a stable aberration corrector although not stable as a lens.

Figure 15 shows a glass lens 300 with a spherical surface 301 used in combination with a separate plastic phase plate 302 for aberration correction. The surface 304 of the plate 302 may include a spherical aberration correction component given by the expression:

$$a \cdot r^4 + b \cdot r^6 + \dots$$

where a is a constant and r is the radial distance from the optical axis (27) G-G.

#### IV. Athermalized Laser Assembly Using Plastic Element

The focusing stability of a conventional laser assembly of a bar-code scanner is affected mainly by thermal expansion of the housing. This is especially true when using, in high volume production, cast metal components (for example, cast zinc) having a large thermal expansion coefficient. Thermal focusing shift then becomes a limiting factor of high-end bar-code scanner performance.

The purpose of the invention is to provide a cost effective, thermally stable focusing solution for high-volume, high-performance, bar-code scanners and particularly for bar-code scanners using the elongated, diverging beam of a preferred embodiment of the present invention.

Figure 16 shows a conventional laser assembly for a bar-code scanner. The assembly includes laser diode 320, glass lens 322, metal lens holder 324, metal



laser holder tube 326, and spring 328. The lens may be attached to the lens holder 324 by glue applied to an annular rim 330. By adjusting the position of the lens holder 324 relative to the holder tube 326 and attached laser 320, the lens is set at the designed distance from the laser. The distance between the laser and the lens focal plane changes with temperature due to thermal expansions of the glass and metal and also due to change of the refractive index of the glass. When using cast metal holders 324 and 326, their thermal expansion/shrinkage plays the major role in focusing change. The thermal change of the distance between laser and the lens flange can be determined as:

$$\Delta x = \Delta T \cdot C_m \cdot L \quad (28)$$

where  $C_m$  is the thermal expansion coefficient of the metal holders, and  $L$  is the distance between laser and lens flanges.

Figure 17 shows a thermally-compensated laser assembly of a preferred embodiment of the present invention. It consists of laser diode 340, glass lens 342, plastic lens holder 344, laser holder tube 346, metal locking ring 348, and spring 350. The lens 342 may be glued to the annular rim 352 of the plastic lens holder 344. When temperature increases, the laser holder 346 will expand, moving lens 342 away from laser 340. A holder 344 is preferably made from a material having a thermal expansion coefficient relatively higher than the laser holder tube 346. For example, the holder 344 may be made from a higher thermal expansion coefficient plastic, while the tube 346 is made of a relatively lower thermal expansion coefficient metal. The lens holder 344, having a length  $L_p$  selected as described below, tends to move the lens back into its original position relative to the laser, and thereby cancel out the effects of thermal expansion.

The length of the plastic holder  $L_p$  can be chosen based on the thermal expansion coefficients of laser holder tube 346, lens holder 344, and glass lens 342. Change of the glass refraction index also can be taken into consideration.

To illustrate a choice of the plastic holder length  $L_p$ , let us assume that the lens does not expand, and its refraction index does not change with temperature. In this case, the amount of defocus can be calculated as

$$\Delta x = \Delta T \cdot (C_m \cdot L_m - C_p \cdot L_p) \quad (29)$$

$$L_m = L + L_p \quad (30)$$

where  $C_m$  and  $C_p$  are the thermal expansion coefficients of metal and plastic respectively,  $L$  is the separation between the laser diode and the lens, and  $L_m$  and  $L_p$  are the flange length of metal laser holder tube and plastic lens holder, respectively. From equations (29) and (30), one can obtain the length  $L_p$  that provides the thermal stability for focusing:

$$\Delta x = 0 \text{ if } L_p = L \cdot \frac{C_m}{C_p - C_m} \quad (31)$$

For example, if  $L=10$  mm,  $C_m=27 \cdot 10^{-6}$  (cast zinc), and  $C_p=65 \cdot 10^{-6}$  (acrylic), then according to equation (31)  $L_p$  should be selected to be 7.1 mm.

In a particular optomechanical design, the plastic lens holder can be replaced by a separate plastic part. Also, length  $L_p$  can be chosen for full thermal compensation including thermal changes of the glass lens material.

**V. Athermalized Optical System For Producing Laser Beams, Including Elongated, Nearly Diffraction Free Laser Beams**

Various of the techniques previously described can be combined to provide an athermalized optical system for producing laser beams, including elongated diverging laser beams of the preferred embodiments described in Sections I and II above. A molded plastic element or component may be used to implement some of the techniques.

Figure 18 illustrates an optical system 400 of a preferred embodiment of the present invention. The plastic element 402 is shown in the system and in the detail Figure 18(a). The system includes a laser diode 404 mounted in a metal tube 406 on the optical axis 0-0. A glass lens 408 is held in position by a compression spring 410 and the plastic element 402. Advantageously, glue may be applied at shoulder regions 412 of the plastic element to maintain the glass lens in position. A metal nut 414 may be employed to secure the plastic element 402 in place.

As shown in detail of Figure 18(a) the molded plastic element 402 is formed with shoulder surfaces 416 to retain the glass lens. Surfaces 418 and 420 are optical surfaces whose design and function is described below. The aperture 422 of the optical system is defined by the surface 418 and bounded by annular edges 424 of the plastic element.

In a more preferred embodiment, a linear axicon is formed in surface 418. The glass lens is a plano spherical lens to provide the necessary optical power. In the most preferred embodiment, the glass lens and separation distance between the laser diode and the lens are selected to provide the  $\beta$  term portion of the wave front deformation set forth in equation (1). Thereby, a diverging, nearly diffraction free laser beam is formed.

Surfaces 418 and 420 may be used to introduce an optical path difference (OPD) between axial ray and a ray with coordinates (x,y) determined by the formula:

$$OPD = C_1 \cdot (x^2 + y^2)^2 + C_2 \cdot \sqrt{x^2 + C_3 \cdot y^2} + C_4 \cdot \cos(C_5 \cdot y) + C_6 \cdot x^2 + C_7 \cdot y^2 \quad (32)$$

where x is the axis in the scanning direction, and y is perpendicular to x. The coefficient  $C_1$  can be chosen to provide compensation for the glass lens spherical aberration as described in Section III above. An element exhibiting such behavior can be generated as a diffractive optical element (DOE). DOE's are conventional optical element and uses of them are described in the '143 patent mentioned above.

Coefficient  $C_2$  can be chosen to generate a laser beam with optimized working ranges and module size ranges as discussed in Section I, above. More specifically, the coefficient  $C_2$  may be chosen to equal  $\alpha$  where  $\alpha$  is the cone angle of the wave front as presented in equation 1.

Coefficients  $C_3$ ,  $C_4$  and  $C_5$  can be chosen to provide desired laser beam stretching perpendicular to the scan lines. The coefficients  $C_4$  and  $C_5$  corresponds to the terms  $W_0$  and  $\frac{2\pi}{\lambda}$  in equation (15) and provide the cosine grating described in Section II above. In a preferred embodiment  $C_3$  is set equal to one. However,  $C_3$  may be adjusted to add some ellipticity to the spot.

Coefficients  $C_6$  and  $C_7$  can be chosen to provide correction of laser astigmatism, additional beam stretching, and to minimize residual optical power of the plastic component.

Length  $L_p$  of the plastic part can be chosen to provide thermo-stable focusing as described in Section IV above.

While aspects of the present invention have been described with reference to preferred embodiments and examples, the invention to be protected is defined by the literal language of the following claims and equivalents thereof.